New Materials and Technologies Available for Use in Industrial Infrastructure

An Overview

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Overview

Construction materials and how they are extracted, produced, transported, utilized, and recycled have significant influence on the economic productivity, environmental impact, and durability and security of the built environment. A great deal of attention has been given of late to the use of innovative materials to enhance the cost-effectiveness, security, and environmental sustainability of public infrastructure, i.e.: our roads, bridges, tunnels, etc. However, industrial infrastructure, a major determinant of manufacturing capacity and the efficiency and quality of associated facilities, is also of critical importance. Industrial infrastructure, which refers to privately owned infrastructure that is for sole use of extracting materials and producing manufactured products, is a complex area of study, drawing on all major fields of the design, engineering, and construction. Moreover, due to the size of the American manufacturing base, different choices in materials and methods used have a significant environmental and economic impact. Therefore, in addition to safeguarding industrial infrastructure, the ability to make more environmentally friendly, sustainable choices without compromising materials efficacy, structural integrity, durability, cost and industrial productivity is of primary importance.

This paper is intended to provide an overview of different types of new materials and technologies that are available. It is not intended to be a comprehensive look at new innovations in materials and technology, rather it is intended to promote a dialog about where research and development has been, where it may go, and the obstacles to innovation that exist. This paper is organized in two main sections. The first provides an overview of several different groups of technologies or processing methods that are either in development or in use. Each of these is examined as an example of what materials, technologies, or methods are available for use in industrial infrastructure, along with a discussion of what makes them innovative, and any energy, economic, or environmental benefits they may offer. This section also examines features of these materials that are advantageous when looking at security issues, including strength, ductility, fracture toughness, fatigue resistance, flexural durability, resistance to abrasion and corrosion, and durability/service life. The second section examines what barriers these emerging materials and technologies face to gain entry to the wider market place, and where efforts would be most productively concentrated.

When looking at the issues surrounding the impact of materials choices for industrial infrastructure, it is important to understand the larger environment in which they will be used. Beyond the normal inquiries into strength and durability, questions must be posed regarding their environmental effects, as well as their potential response to catastrophic events, man-made and otherwise. New technologies and high-performance materials are being developed to meet these needs, offering creative and innovative solutions to long-standing problems. These materials and technologies range from corrosion-resistant alloys to rapid-set concrete repair products to seismic isolation bearings. They all offer benefits, whether to structural stability, the environment, or to the maintenance and repair process.

Construction is a significant consumer of energy directly, has a major impact on overall energy use in the economy through the buildings and facilities it creates, and offers the most significant opportunity for utilizing the waste and by-product materials from other industrial and energy conversion processes. Because of these factors, the industry has very high potential in changing the patterns and levels of energy consumption, in reducing waste of materials, and in creating sustainable infrastructure, both public and industrial, throughout the entire economy.

In other words, constructed infrastructure can enhance the productivity of the entire economy if designed and built well and effectively; conversely, it can serve as a drain on that productivity if designed and built poorly. Because of this, new concepts, tools, and methods in the design and construction industry can have significant contributions to energy efficiency, mitigating global climate change, and generating sustainable development. This leverage is especially relevant as we consider the new, overarching issue of infrastructure security – our society cannot design truly secure infrastructure without incorporating sustainability, energy efficiency and economic productivity into that design.

Technology Roadmaps for various energy-intensive manufacturing industries have been produced under the auspices of the Department of Energy Office of Energy Efficiency and Renewable Energy (DOE-EERE) Industrial Technologies Program's Industries of the Future (IOF) strategy. These Roadmaps show a great deal of common ground, and many ideas that may be applicable to the construction industry. The repeated appearance of such goals as increased environmental sensitivity, increased economic efficiency, greater emphasis on collaboration, and removal of barriers to research and development, may all be seen as indicative of larger trends. As previously stated, the construction industry is in a unique role, being both a customer and a provider of goods and services to the IOF industries. Given the link between the construction industry and the lumber, aluminum, glass, steel, metal casting, cement and mining industries, to name a few, it must therefore be responsive to these trends. Therefore, turning attention to innovations in materials and methods available is essential if the design and construction industry is to maximize its symbiotic relationship with the industries of the future.

<u>What Are the Criteria?</u>

Before discussing the new materials and processes available, it is essential to define what characteristics are being sought. New materials and production processes may offer a wide range of benefits, from lesser environmental impact, to increased strength and durability, to economic benefits. For the purposes of this writing, criteria defined by the Civil Engineering Research Foundation's High Performance Construction Materials and Systems (CONMAT) program will be used. This program was a collaborative effort across the design and construction industry that looked at what characteristics would be desirable in new materials in order to set forth industry goals and aims. In addition, the program intended to encourage innovation by looking at high-performance generations of traditional materials, as well as new technologies and materials.

The criteria set out describe characteristics desirable in infrastructure itself, but in order for infrastructure, industrial or otherwise, to possess a certain suite of characteristics, its components must as well. These characteristics include the following:

- Superior strength, toughness, and ductility
- Enhanced durability/service life
- Increased resistance to abrasion, corrosion, chemicals, and fatigue
- Initial and life-cycle cost efficiencies
- Improved response in extreme events such as natural disasters and fire
- Ease of manufacture and application or installation
- Aesthetics and environmental compatibility
- Ability for self-diagnosis, self healing, and structural control (CERF 1994)

In light of the terrorist attacks of September 2001, improved blast resistance as well as improved structural and flexural integrity under extreme demands may be added to this list.

While these characteristics may seem intuitively desirable for industrial infrastructure materials, they address significant weaknesses that have been an issue for the design and construction industry in the past. However, they also offer insight into the industry's ability to think beyond its current boundaries and to continually strive for improvement, utilizing its resources to fully pursue innovative ideas.

Major themes that have emerged with respect to sought-after characteristics include corrosion resistance and improved strength. This has been achieved both through new ways of processing and working with older materials, as well as the creation of new materials, smart materials, alloys, and composites.

In the following text, several specific products and methods are referred to. This is not intended to serve as an endorsement of any particular product or company, nor is it intended to imply that a particular product is the best option available. They are mentioned solely to serve as examples and illustrations of what is available in the marketplace for use by industry.

What Materials Choices Are Available?

There are a number of new materials available with different advantages, and containing different combinations of the characteristics described above. The following section provides an overview of the types of materials available and is not intended to show preference for any particular technology application. These innovations range from improvements in steels and intermetallic compounds that are highly corrosion-resistant to new cement production techniques that are more energy efficient and produce fewer emissions. Each category has the potential to provide new insight into innovative methods and techniques that will be available, and open new doors for advancement and improvement in industrial infrastructure.

Fiber Reinforced Polymers

Fiber reinforced polymers (FRP) have been gaining in development and application in recent years. They are made of fibers embedded in a polymeric resin, and have been used in place of steel reinforcement for concrete structures. FRP is made of noncorrosive and nonmetallic materials, which means that it is not subject to the corrosion issues that are common to steel. In addition, it has been shown to possess high tensile strength, and the newer generation of FRP bars can provide adequate ductility, which makes them suitable for structural uses. In addition, preforming pieces for on-site construction can save time and energy and enable structures to be erected very quickly, cutting down on labor costs. According to the Construction Industry Institute, glass FRP bar may be a suitable alternative for steel reinforcing in architectural concrete, concrete exposed to de-icing salts, exposed to marine salts, or used near electromagnetic equipment (CII 2002).

FRP can be used both for repair or freestanding structural purposes. Unlike other materials that may be used for repair and maintenance, FRP may be put in place permanently, without concern of replacement necessitated by corroded materials. In addition, it does not require significant amounts of demolition be done before repairs can be made (CII 2000). FRP "fabric" or sheets can be wrapped around concrete columns or beams to increase stiffness and durability. The sheets are glued to the structural elements using powerful adhesive, requiring less time and effort for installation than steel plates. FRP rebar is being considered for use in place of steel rebar, as it has been shown to possess high tensile strength and toughness that would make it a structurally sound replacement. One of the barriers for use of FRP, which will be discussed in greater detail below, is its high cost per unit as compared to steel. However, the types and amounts of fibers and resins used, as well as the quality, will not only determine price of the material, but also the structural and mechanical qualities of the resulting polymer.

Benefits of FRP:

- *Lightweight*
- *Non-corrosive*
- *High tensile strength*
- *Can be used for repair or free-standing structures*

Research and testing is underway in a variety of venues domestically and overseas. For example, the "ConFibreCrete" European research network, together with the *fib* (International Federation of Concrete) TG 9.3 and ISIS Canada are organizing round robin tests for FRP reinforcement. Information on that project is available on the Internet at http://www.shef.ac.uk/~tmrnet/rrt/.

Concrete & Cement Products

The repair and maintenance of concrete structures is a significant budgetary item for both public infrastructure and industrial infrastructure. The length and difficulty of the repair process can both contribute to the costs, which accumulate rapidly. In addition, needed structural repairs may constitute a security and safety risk. In addition to the myriad changes taking place in the global economy, industry must now also contend with safety and security issues that present challenges from both an engineering and an economic standpoint. Emerging concrete technologies provide an opportunity to reduce construction and repair times, as well as ensure that projects remain cost-effective.

SIMCON

Slurry Infiltrated Mat Concrete (SIMCON) is one of a group of materials known as High Performance Fiber Reinforced Cementitious Composites (HPFRCCs). These materials have been developed in recent years to respond to the cost of creating and maintaining infrastructure. They have been demonstrated to provide greater strength, seismic performance, durability, and crack control when compared to conventional concretes. In addition, certain HPFRCCs such as SIMCON may be applied more rapidly and with less expense than conventional methods (CII 2000).

Benefits of SIMCON:
- *High strength*
- *Good crack control*
- *Rapid application and installation*

SIMCON is installed using manufactured mats of continuous stainless steel fibers. These mats are delivered to the site in large rolls, and then need only to be cut to size and placed in or around the formwork. After the mats are installed, they are injected with a dense cement-based slurry. The fiber mat allows for simplified fiber placement, and allows a far lower fiber volume than SIFCON (Slurry Infiltrated Fiber Concrete) (Krstulovic-Opara et al, 1997.) SIMCON has been used both for retrofitting purposes and for the construction of composite structural systems.

This technology can serve the needs of industrial infrastructure in many ways, offering faster installation and construction, as well as reliable retrofitting and repair options without compromising on quality or strength of materials. Extensive testing on SIMCON has demonstrated high strength, good crack control, and excellent flexural behavior. Due to its fiber mat construction and the resulting flexural advantages it offers, it may also be beneficial for use in areas where seismic activity is a concern.

Rapid Repair Technologies

An important application of advanced materials is the repair of concrete structures in place. This can offer a significant means of improving the cost-effectiveness and service life of industrial infrastructure. A number of manufacturers offer rapid repair products and there are active research programs underway. The National Institute of Standards and Technology (NIST), Building and Fire Research Laboratory (BFRL) is a particular focus of this research (see NIST report NISTIR 6402 ***Predicting the Performance of Concrete Repair Materials***, January 2000). This work was sponsored by a group of industries including:

- Conproco Corp.
- Master Builders, Inc.
- Sika Corp.
- Structural Preservation Systems, Inc.
- W.R. Grace & Co.

CERF has also worked to evaluate specific rapid repair materials. A recent example, which has specific energy and environmental benefits, is Ceracrete. Ceracrete refers to a chemical process technology that has been used to create three separate rapid-set concrete repair products, Pavemend, Laymend, and Vertimend. All three products contain high percentages of recovered materials including coal ash, municipal solid waste ash, foundry sand residue, dredge material, and flue gas desulfurization by-products among others, providing environmental as well as structural benefits.

The Ceracrete products are a group of phosphate cements that are unique in their use of a high degree of residual materials and waste products mentioned previously. Depending on the intended use of the product, which can range from sand stabilizers to rapid repairs for airport runways, these recovered materials can be used at concentrations of up to 80% by weight. For rapid repair uses, the recommended amount to still maintain high strength is 40% residual materials.

Benefits of Ceracrete Rapid-Repair Cements:

- *High percentage of waste materials recycled*
- *Zero-shrinkage materials*
- *Rapid set time*
- *More durable and less expensive than traditional epoxies*
- *More resistant to liquids over other concretes*

In testing and use with the US Air Force, Ceracrete products have been used to repair runway potholes, and have been able to support full traffic 45 minutes after application. In addition, they can be used in a wide range of temperature extremes, depending on the length of mixing time before the product is applied. Due to the exothermic reaction that takes place during mixing, there are no additives necessary to cope with temperature extremes, just a longer required mixing time (Mike Riley, pers. comm.) In addition, these are zero shrinkage materials, so that repairs made in freeze-thaw environments, even during winter months, will be more durable and require far less maintenance than traditional patch materials that cannot match the strength and hardness of traditional materials. In addition, the new generation of products has a range of workability times, which allows them to be used for more than just rapid repairs. Epoxies have been traditionally used for rapid repairs of roads and runways, but the price per unit is usually high compared to cementitious materials.

One particular way in which it may specifically apply to industrial infrastructure use is for use on concrete pipe, both as a repair material and to make precast materials as well. Ceracrete products have a much finer pore structure than a Portland cement concrete, and are therefore far more resistant to liquids, such as water. If water is able to permeate concrete structures, it can result in structural weakening, particularly in structures using steel rebar, which is susceptible to oxidation. In addition, this allows them to protect rebar better than traditional concrete. Ceracrete is a pH neutral product, and does not offer the same alkalinization benefits to rebar that a Portland cement concrete would, but when applied it completely coats the rebar, offering protection from corrosion. In addition, since it is pH neutral, it does not corrode aluminum in the way that Portland cement would (Mike Riley, pers. comm.)

Ceracrete products are currently being used by the United States military in Afghanistan for runway repairs and other rapid-repair needs. Its wide temperature tolerance has made it suitable for use in desert climates, which are characterized by extreme fluctuations in temperature.

Materials such as Ceracrete also offer several benefits with regard to environmental and economic impact. First and foremost, the use of recycled and waste materials offers a renewable way to keep waste products out of landfills in a stable way, where they can serve a productive use. In addition, the creation process usually results in far fewer particulate emissions, as the process is one of blending fine-grained powders as opposed to the conventional process of creating Portland cement. The World Business

Council for Sustainable Development (WBCSD) recommends cements with lower clinker content, such as composites that use fly ash and other reclaimed products, as one method for reducing CO_2 emissions by (Humphreys & Mahasenan 2002).

Total project costs can be further lowered through the use of rapid repair materials due to the reduced frequency of replacement, and the increased strength, hardness, durability and temperature tolerance over traditional concretes and patches. Furthermore, the most significant cost factor in the maintenance and upkeep is time, whether time of the construction and maintenance workers to attend to the repair at hand, or time during which a building, road, or pipe will be out of use due to repairs.

Materials such as Ceracrete also offer potential for use in security applications. One potential use currently in development is as appliqué armor for buildings. It would be used to form a lightweight tile that would then be backed by rubber and attached to the exterior of structures with security concerns, such as embassies. If gunfire or some other type of explosion hits an individual tile, it serves to buffer the structure and absorb the shock. The shattered tile may then be simply removed from the exterior of the building and replaced. The advantage of a system such as this one is that the tiles are designed to look like simple architectural elements, yet they serve a valuable security function as replaceable shock absorbers and building armor. A similar system is already in use for some military vehicles using ceramic tiles (Mike Riley, pers. comm.)

Innovative Cement Manufacturing Processes

Another significant means of producing advanced materials is to re-engineer or enhance the manufacturing approach to create a better product. One such approach is "energetically modified cement", (EMC). EMC is a patented process that involves "intergrinding a mixture of ordinary Portland cement (OPC) and materials such as fly ash, blast furnace slag, or quartz sand through multiple high-intensity grinding mills (typically vibratory or stirred ball mills) (Placet & Fowler 2002)." The resulting product, due to the grinding method used, has increased surface activation and allows a higher proportion of pozzolan to be used without compromises in early material strength. The term pozzolan refers to any fine-grained material that reacts, in the presence of water, with calcium hydroxide and alkalies to form cementitious compounds. It is a mineral additive that may be used as a supplement to standard Portland cement and create additional binders in a concrete mix. In testing conducted in the United States and Europe, concretes made from EMC performed at least as well as those made from OPC, and in some cases they performed better (Placet & Fowler 2002). The resulting strength, hardness, and durability of the product will ultimately depend largely on the combination and proportion of ingredients used in the cement.

Benefits of Energetically Modified Cements

- *Increased surface activation*
- *A higher proportion of pozzolan may be used without compromising strength*
- *A high percentage of recycled materials may be used*
- *Requires far less energy to create than traditional cements*

WBCSD estimates that, despite increased capital costs for the extra processes required to create EMC, it would likely be less costly to produce than OPC due to the high proportion of recycled, reclaimed, or waste materials used in the process. The use of these materials also provides environmental benefits, finding stable reuse for them and reducing greenhouse gas emissions in the process. The manufacturing of Portland cement, as well as mining for its components, produces tremendous amounts of CO_2 and raises issues of residual environmental contamination as a result of open pit mining operations. The addition of fly ash, slag, or other materials, will necessitate less mining, less energy expenditure, and less gasification of CO_2 (Horst 2001).

> *"Manufacturing Portland cement is one of the most energy intensive processes of any industrial manufacturing process. The extreme heat required to operate kilns creates a significant demand for energy. Approximately 6 million BTUs are required to produce one ton of Portland cement. Over the past several years, process changes and techniques have been introduced to improve energy efficiency in kiln operation and reduce energy demand…90 million tons of coal were burned and 68 thousand tons of waste were burned for cement production in 1997."*
>
> Scot Horst, "Some Basics About Substituting Pozzolans for Portland Cement in Concrete"

Manufacturing Portland cement is an extremely energy-intensive process, with approximately 6 million BTUs required to produce 1 ton (Horst 2001). While there have been improvements in industrial manufacturing processes that have reduced the energy demand of Portland cement production, it is still quite a costly process, both energetically and financially. Given the necessary expenditure to manufacture Portland cement, the use of reclaimed waste materials in its place will greatly lower the amount of energy and money invested in cement production. In addition to environmental benefits, WBCSD also found that the use of fillers such as fly ash could increase durability through a number of chemical processes, such as improving alkali-silica reactivity, as well as permeability to gas and liquids (Placet & Fowler 2002).

Metals and Intermetallic Alloys

Improvements in technology for metals and intermetallic alloys have greatly increased in recent years, resulting in a new generation of steels and other alloys that are lighter, stronger, have increased weldability, are more corrosion-resistant, and more energy-efficient. These features, in turn, result in products that will be more cost-effective and longer lasting for builders, building owners and operators.

Fe-3Cr-W(V) Ferritic Steels

There are two main groups of stainless steels, austenitic and ferritic. Austenitic steels are more corrosion-resistant and are the largest class of stainless steels produced. They are characterized by the presence of nickel and a higher proportion of chromium than ferritic steels. Ferritic steels, the second largest class, are best suited for general corrosion applications and those done at high-temperatures.

> **Benefits of New Ferritic Steels:**
>
> - *Post-welding heating treatments are unnecessary*
> - *Higher tensile strength*
> - *Weight reductions*
> - *Improved impact properties*

Current research and development in steels has yielded significant improvements that are applicable to several major industries. The chemical industry in particular stands to benefit from the innovations being made with ferritic steels, given the temperature extremes that are frequently necessary in production. Current construction of chemical processing equipment using steels composed of iron, chromium, and molybdenum (Fe-2.25Cr-Mo) requires post-welding heating treatments that cannot be performed on-site, limiting the adaptability of the product. New alloys composed of iron, chromium, and tungsten (Fe-

3Cr-W(V)) are being developed which may eliminate the need for post-welding heating treatments, and which also offer higher tensile strength, weight reductions, and improved impact properties (DOE-EERE Industrial Technologies Program 2002). These advantages can serve to simplify the manufacturing process, saving energy and money through a decreased need for heating the steel after welding, and allowing more modifications to be made on-site, resulting in a product that best fits the needs of the user.

Corrosion resistant alloys

Ceramic-metal composites offer a range of advantages for industrial infrastructure by combining the best properties of each material, offering benefits regarding their stiffness-to-weight ratio, facture toughness, high-temperature stability, and corrosion resistance. They can serve in a number of functions, either as independent materials or as coatings to prevent corrosion and deterioration of other, more susceptible materials. One technique currently being explored for use in creating these alloys is reactive metal penetration (RMP) of dense ceramic preforms (Loehman et al, 1998). This option has several advantages over traditional use of ceramic composites, which tend to be very costly to produce and apply, and have yet to demonstrate reliable performance. RMP offers a less costly way to create composites, through the use of relatively inexpensive ceramic preforms made to near net shape, which reduces the amount of grinding and machining operations necessary to create a finished product (Loehman et al, 1998). These processes can also be quite energy-intensive, and their reduced necessity results in increased energy efficiency in the process, and minimize waste.

Benefits of RMP:
- *Offers the benefits of ceramics with less expense and more reliability*
- *High corrosion resistance*
- *Changes to certain characteristics of the product can be made more easily than with traditional ceramics*

A potential offshoot of work with RMP is in finding new materials and better processes for use in the metal-processing industry. The development and understanding of reactive and non-reactive compounds can illustrate the best materials for use in the production of metals, to produce the highest quality products. In addition, these composites can be examined for use as coatings for metals that may be vulnerable to the elements, such as aluminum and some steels. Preceramic binders can mix well with a wide variety of fillers, and will then adhere well to metals, forming highly corrosion resistant coatings (Loehman et al, 1998).

RMP offers several benefits over traditional composites. Typically, when optimizing certain characteristics of composites, changes in process or formula are necessary. These changes can be very costly, and result in reduced efficiency, both energetically and economically. In RMP, changing the forerunner with minimal, if any, change to the process can modify the final composite. Changes in preform composition can dramatically affect characteristics of the resulting composite, such as strength, toughness, and reliability (Loehman et al, 1998).

High-performance steel

There have been continual advances in steels over the years that have resulted in higher strength products. However, these products have not been without their shortcomings, and frequently require more welding control and fabrication processes (CII 2000). Because of these shortcomings, these higher strength steels have received less use in the general marketplace. In the mid-1990s, the Federal Highway Administration, American Iron and Steel Institute, and the Department of the Navy began a cooperative project to develop steels that would posses increased strength, without sacrificing weldability and overall performance. These new grades of steel, HPS-485W or HPS 70W use alterations in conventional chemical composition to create a material that is lighter, more durable, has a higher fracture resistance, and has a smaller environmental impact, with half the carbon content and 1/10 the sulfur content of conventional steels (Mistry, undated; CII 2000). HPS is virtually 100% recyclable, adding to its environmental benefits. Furthermore, its increased resistance to corrosion extends its useful lifetime, thereby reducing the need for frequent replacement and enhancing its cost profile.

Benefits of HPS:
- *Lighter than conventional steel without compromising strength*
- *Good weldability*
- *High fracture resistance*
- *Less environmental impact due to lower levels of carbon and sulfur used*

In 2001, high performance 70 ksi steel was used on a 370 ft., three span bridge constructed by the Nebraska Department of Roads. While a concrete option was also bid for the project, the steel bid came in at a lower fee, despite the higher price common to HPS. In this instance, where both conventional 50 ksi steel and high performance 70 ksi steel were used, it was found that the increased strength of 70 ksi steel lead to lighter, thinner components, which reduced the overall cost for the structure (Van Van Ooyen 2002). Although this project deals solely with public infrastructure, NDOR's experience with HPS serves as a valuable lesson for industrial infrastructure as well. Although costs per unit of HPS may exceed that of conventional steel, NDOR was able to construct the bridge using HPS selectively, and only where there was a significant advantage in terms of price or performance. This selective approach was critical to the success of the project, allowing it to be bid competitively against other materials that may have, at first glance, seemed to be the more obvious choice in terms of cost.

Other Corrosion Resistant Alloys

There are several other types of corrosion resistant metal alloys that are being used that can maintain strength and withstand temperature extremes as well. Haynes International, Inc. and Crucible Compaction Metals are both working to create lines of alloys, primarily nickel-based, that are suitable for use in paper, chemical, and petrochemical industries, among others.

The Hastelloy ® products, manufactured by Haynes, are designed to be resistant to a wide range of corrosive chemicals, such as hydrochloric, sulfuric, and hydrofluoric acids, among others. These nickel-based alloys have also shown high crack corrosion resistance, resistance to pitting, and may be used in either oxidizing or reducing environments. There are specific alloys that have been developed for more specific purposes and processes, such as their Hastelloy ® N-alloy, developed specifically for use in containing molten fluoride salts (Hayes International 2003).

Crucible Compaction Metals has developed a line of corrosion resistant, primarily nickel-based alloys, also for use in a wide range of highly corrosive environments, ranging from deep sour gas wells and chemical manufacturing to nuclear power industries. Sour gas contains measurable concentrations of hydrogen sulfide, thereby producing highly corrosive conditions when drilled for. Their alloys are available in several different forms, including near net shapes, which will reduce the post-manufacturing demands on the user.

Self-Diagnosis, Mitigation, and Repair Technologies

One of the most intriguing fields of innovation in design and construction is the advancement of diagnostic, mitigation, and repair technologies. These are sometimes called “smart materials”. Use of these products allows building owners and operators to more closely monitor the structural integrity of their facility on an everyday basis, and particularly after a catastrophic event, when in-person monitoring or evaluation may be extremely hazardous. Some of the most advanced work currently underway is focused on materials such as fabrics, plastics, and composites that are not often considered to be in the infrastructure arena; however, the research underway indicates that rapid advances in applying that work to industrial infrastructure can be expected in the coming decade. While these are not materials, per se, these devices do represent exciting advances available for use in industrial infrastructure. The technologies described below are examples of smart materials and systems that are ready for use now.

In the case of seismic isolation systems, they have proven to be very practical means of mitigating the potentially damaging effects of earthquakes, helping to not only protect structural integrity but also protect the contents of the building by dampening the acceleration of the floor during the earthquake. Other available technologies are particularly useful to industries that work with hazardous materials or deal in temperature extremes where structural integrity of their facilities is a matter of public safety as well as the safety of their employees. Furthermore, diagnostic or self-repair devices may alert owners and operators to potentially hazardous situations, such as chemical or petrochemical leaks, in advance of a crisis situation, thereby allowing sufficient time for an adequate and appropriate response. They may also allow for decreased recovery time and increased resistance to catastrophic events such as natural disasters or attacks.

Seismic Isolation Bearings

Seismic events can lead to structural failure on a massive scale, and pose as much of a threat to industrial infrastructure as to public infrastructure. Conventional design and construction has traditionally made use of a ductility-design philosophy, relying on strength and ductility of the foundational elements of the building or bridge. Seismic isolation bearings have several advantages, as they help to avoid or minimize structural damage, while maintaining serviceability (CERF 1999). They serve to isolate the ground motion from the structure housing the bearing, thereby relieving demands on structural elements that would otherwise be damaged by the internal forces resulting from the ground acceleration. Their energy dissipation capabilities, in combination with the flexibility that they add to a structure, allow a building to respond to a seismic event without incurring deformation of structural components beyond their elastic capacity. In addition, they direct stress away from the weaker elements and reduce the earthquake force demand to help preserve structural integrity. Furthermore, their ability to minimize relative structural displacement and reduce floor acceleration results in reduced losses of equipment and other non-structural items within the structure itself. There are four main reasons to employ seismic isolation devices: enhancing structural performance, enabling post-earthquake operations, protecting buildings and their contents, and preserving historic buildings and districts (Naaseh 2001).

Before deciding to utilize seismic isolation devices, there are several issues that must first be resolved to ensure that it is appropriate for use in the proposed location. First, the potential efficacy of the isolation device must be reviewed based on issues of site and materials suitability. In addition, issues such as bearing placement, flexible connections for utilities that cross the isolation line, design of elevator shafts and stairwells, and protection of the bearings must all be taken into account to determine suitability of use (Naaseh 2001). There have been many examples of bearings being used in retrofitting operations, such as the Salt Lake City and County Building in Salt Lake City, Utah, City Hall in San Francisco, California, and the Oakland City Hall in Oakland, California. In each structure, there were issues regarding older building techniques and historic preservation to be accommodated. In an industrial setting, the latter is unlikely to be a high concern, but it does provide a lesson in the ability to retrofit seismic isolation capability in older plants, storage facilities, and factories. Therefore, not only can isolation bearings serve to benefit industry by reducing the damaging effects of earthquakes, they can also be installed as a retrofit so as to minimize the need for structural replacement in older industrial infrastructure.

Benefits of Seismic Isolation Bearings:
- *Reduced floor acceleration*
- *Protection of structure and contents*
- *Improved building performance*
- *Adaptable to new and old buildings*

There are three main types of seismic isolation systems, each with unique characteristics. The first group, elastomeric isolation systems, is able to provide horizontal flexibility as well as damping, or energy dissipation through alternating layers of steel plates adhered to natural or synthetic rubber. There are differences among the various types, such as lead-rubber bearings that have a lead core, and high dampening rubber bearings that add fillers to the rubber (CERF 2001, 1999). The second group, sliding isolation systems, are made from two dissimilar materials that slide against each other, frequently using a material such as Teflon to lower friction. They also have mechanisms to limit displacement by limiting the amount of sliding possible. The third group is known as hybrid isolation systems. They use a variety of independent components to provide energy dissipation and flexibility (CERF 1999).

For example, an elastomeric isolation system, by Seismic Energy Products, was tested through CERF's Highway Innovative Technology Evaluation Center in 2001. The system tested was a circular multidirectional elastomeric bearing reinforced with steel and a lead plug insert. The inner layers of rubber and the lead core are meant to deform in a seismic event as a way to absorb energy and protect the structural integrity of the building. The bearings were tested for such features as range, capacity, resilience, performance under service and dynamic loads, energy dissipation, functionality in extreme environments, resistance to accelerated aging, predictability of response, fatigue and wear, and size effects. While there are no defined standards for displacement with seismic isolation bearings, the target range was from six to twelve inches, depending on the axial load capacity. The bearings completed the tests without failure, showing no significant problems with exposure to high temperatures and increasing harmonic loading in excess of the target ranges (CERF 2001). In summary, these bearings completed each test successfully, indicating the value and merit of an elastomeric isolation system for protecting structural integrity, even under further environmental stress.

Another type of seismic isolation device on the market is the Friction Pendulum ™ by Earthquake Protection Systems. The bearing is intended to be installed between a structure and its foundation, and is composed of a concave "lid" that has a self-lubricating composite liner and an articulated slider. During an earthquake, the slider moves along the concave surface, reducing the ground acceleration to a pendulum-like movement in the structure, greatly minimizing the force applied to the building. They have been designed to perform in earthquake events up to magnitude 8, resulting in a substantial savings of human life and property value (Zayas 2000). These bearings are very resistant to the effects of aging and temperature changes and in some cases have been manufactured to accommodate displacement of 53 inches and vertical loads of 30 million pounds (CII 2001, Earthquake Protection Systems 2000).

These devices could be of particular interest to industries located in seismically active regions, such as the west coast of the United States, for example. They can reduce damage sustained during seismic activity, thereby offering economic benefits, as well as benefits to structural stability and soundness.

Leak Detection systems

The EPA has monitored underground storage tanks since the late 1980s in an effort to ensure that they maintain their structural integrity and do not leak their contents into the surrounding environment, possibly triggering environmental contamination and public health problems. Industry, particularly the chemical and petrochemical industries, can potentially avoid costly and wasteful accidents by employing the technology to monitor leaks in storage tanks.

Leak detection systems may use a variety of means to perform their functions. One such technology is a Low Range Differential Pressure (LRDP) Leak Detection System, currently produced by Vista Research, Inc. It is a mass-based leak detection system that can quantitatively measure leaks in gallons per hour. It was initially designed for very large underground storage tanks, such as the Department of the Navy's Red Hill tanks buried near Honolulu, Hawaii which each hold approximately 12.5 million gallons of fuel. However, testing has shown that the system also works well for smaller tanks, and offers greater precision regarding tanks of a wider range of sizes than what conventional means can offer. The key component of the system is a vertical reference tube that spans the full height of the tank, and is filled and emptied along with the tank. When the level of fluid in the tube and tank are the same, the pressure differential between the two measures zero. Sensors in the tube can detect changes in that pressure differential, which is interpreted

Benefits of Leak Detection Systems:

- *Prevention of environmental contamination*
- *New technologies are very sensitive, enabling early detection*
- *Early detection can result in prompt repair and cleanup, minimizing any fines incurred as a result of a leak*

as a leak. In addition to detecting a leak, the sensors can further determine the rate at which fluids are leaking from the tank. The system may be installed permanently, or it can be van-mounted and used for scheduled testing, offering flexibility and greater ease of monitoring at multiple tank sites.

The system can account for natural losses or gains such as evaporation, condensation, thermal expansion, or thermal contraction. Furthermore, the LRDP system scales with the surface area of the tank, allowing for greater accuracy at a range of sizes. This level of detail allows for a more accurate reading of the tank status, allowing for owners and operators to better maintain their facilities, avoiding both environmental and economic problems.

One important feature to note is that LRDP systems may also be adapted for use in above ground storage tanks, which are not currently regulated by the EPA. Leaks from above ground storage tanks may, however, be just as damaging with respect to public health, the environment, and the economic health of their owner and operator. They are more difficult to monitor properly as they are more subject to temperature fluctuations and corrosion due to external factors that can compromise structural integrity (CERF EvTEC 2000). The costs of the technology vary with respect to where the system is installed and will be unique to the needs of the user. In addition, there has been interest vocalized in attempting to adapt the LRDP system to pipeline and hydrant systems

Acoustic monitoring technologies

Acoustic monitoring technologies are a non-destructive method for evaluating prestressed concrete structures. When installed, they can measure deterioration and corrosion of wires or strands at localized areas of corrosion. They may also be used to determine the rate of corrosion, which not only provides valuable data for future use, but can also alert engineers to the time remaining to deal with the system failure efficiently and effectively.

Acoustic monitoring technologies can take several forms. An acoustic monitoring system, such as SoundPrint ® by Pure Technologies, allows for continuous, non-destructive monitoring of entire structures through the use of sensors mounted on the structure that are capable of detecting the acoustic energy released by the breaking of a prestressed wire (Elliott, McCarthy 1998). This data is then sent to a central monitoring unit, where it is interpreted and analyzed. This technique allows the building owners and engineers to focus on preventive measures and maintenance, instead of having to cope with an unforeseen structural failure. In addition, replacing strands as they break can serve as a gradual way to upgrade the structure over time, while spreading out expenditures. Furthermore, such monitoring offers the opportunity to collect fine-scale data on corrosion rates and other factors affecting the building life cycle.

Benefits of Acoustic Monitoring:
- *Non-destructive installation*
- *Allows for early detection of compromised structural integrity*
- *Early detection enables catastrophic structural failures to be avoided.*

Another type of non-destructive testing is that of using electromagnetic acoustic transducers (EMAT). EMATs monitor acoustical waves through a contactless electromagnetic probe that can detect sound waves, or changes in patterns, ultrasonically. This method does not require a coupling medium, thereby reducing the number of possible complications that can be seen with techniques that require wet coupling. EMATs enable easy control of orientation of the ultrasonic beam, which allows the monitors to be shifted to most accurately detect sound waves (Aliouane et al 2000). In addition, they can contain flaw discriminators that allow for false alarms to be detected with a through-wall depth of 10% (CII 2000), meeting code requirements for such self-monitoring systems while ensuring that severely flawed materials are recognized as such. EMATs have been considered for use as replacements for the two most common types of non-destructive evaluation methods, magnetic particle testing for surface inspection and radiography for volumetric testing. They offer a higher temperature tolerance, enabling inspection of welds soon after they are made, can be used more quickly, and are not subject to the misdiagnoses that occur with both other methods. Currently, EMATs are being used for non-invasive pipeline inspections (CII 2000), and could provide the chemical and petrochemical industries, among others, with a valuable tool to detect flaws in materials before they become problems.

Despite myriad possibilities for advances in materials and technologies, barriers to innovation still play a strong role in determining the speed with which these breakthroughs may enter the marketplace. Creativity is essential to finding ways to address these barriers and move innovation into practice.

Barriers to Adoption of Materials Innovation

There are myriad barriers to innovation in the design and construction industry that have become inherent problems familiar to designers and builders. They range from issues of cost and liability to market cycles and a lack of established reliability for some products. In order to benefit from the wealth of knowledge and innovation that is currently being developed, it is advantageous for the owners of industrial infrastructure (i.e., the customers of the design and construction industry), to begin a dialog with the design and construction industry about ways to dismantle or overcome these barriers. The following narrative provides some background for that dialog

Lack of Resources

The design and construction industry traditionally does not invest heavily in research and development, devoting only 0.5% of its revenues in aggregate to such endeavors (CERF 1997). This results from a combination of factors such as low profit margins financial risk, rapid financing and turnaround of projects, extreme fragmentation of the industry, and unstable economic cycles among others. With so little devoted to R&D, the industry is hampered due to a lack of resources adequate to pursue innovation. In addition, “approximately 85% of all design and construction firms employ less than ten people (CERF 1997)”, which indicates that such small businesses may not have the financial ability to devote any significant funds to innovation or the market share to make it worthwhile.

Fragmentation in the Decision-Making Process

The small size and limited resources contribute to, and are exacerbated by, significant fragmentation in the project decision-making process. Since the builder is not typically the owner and operator of the building, there is a reduced incentive to take life cycle costs into account; therefore short-run savings can take precedence over lowered life cycle costs resulting from improved performance or durability. Even more to the point, the designer and builder are often from different firms, selected by different procurement processes, with little opportunity to interact and no incentive to optimize productivity, cost-effectiveness, and innovation over the overall project.

Lack of Performance Data and Information

If a product or technology does not have an established history of use or profitability, the risk of additional capital expenditure is often avoided. In some cases, building code makers have not yet approved these new materials for use and as such they must undergo more testing before being given entrance to the wider marketplace. If the proof of reliability and consistent performance is lacking, the incentive to invest in a new technology and push for regulatory acceptance is not there. The cost of obtaining the performance data and putting it in the hands of the decision-makers is a significant barrier to commercializing innovative technology and products.

Prescriptive Codes and Standards

Designing materials, processes, and technologies that meet the requirements of complex building codes can be a frustrating and discouraging process. Although there are ongoing attempts to adopt performance-based codes, most codes are prescriptive. These were originally designed to ensure quality, but have become significant impediments to new ways of doing things. Streamlining the code process and making it innovation-friendly may be one way to mitigate this barrier to innovation. Performance-based codes offer the potential to ensure quality while encouraging innovation.

Liability

Issues of liability can act as powerful deterrents to innovation. The design and construction industry is responsible for avoiding risks to public health, the environment, and worker/user/operator safety. Companies are rightly very hesitant to place themselves in the path of a potential lawsuit. Therefore, a product or technology that has not been extensively tested for safety and that does not have a substantial track record is unlikely to be picked up, particularly by smaller companies that would not be able to withstand paying a large settlement.

Risk

Closely related to liability, risk for a company takes many forms, and the construction industry is especially risk averse. The business environment in which a construction company or designer operates includes low profit margins, significant responsibility for public and worker safety, the need to maintain predictable schedules and costs, etc. This creates a situation in which relatively small uncertainties can mean the difference between success and failure – of a project or the business. Uncertainty in the performance of a technology or product is an additional risk that few businesses are willing to take without the potential for significant compensation.

Inconsistent Metrics

Finally, there is a lack of coherence and consistency in the measurement of success, especially with regard to verification and approval of new technologies. This is due, in part, to the fragmentation seen in the industry itself, as well as its regulatory framework and oversight mechanisms. There are numerous players for a single project who may have different ideas about how a project should be run, different attitudes regarding innovation or the use of new materials, and different ideas about the value of short-run versus long-term savings. With regard to the approval of new technologies, there is no central agency or group that bears the responsibility for testing, evaluating, and approving new technologies. Approval for use must take place on many different levels and can be a redundant process, providing further frustration and disincentive. A more transparent and streamlined process of approval is needed to enable new technology to be brought to use more easily.

Moving Forward

In the area of industrial infrastructure, there may be significant potential for overcoming the barriers to innovation that have plagued public infrastructure. Industrial owners often have more flexibility and understanding of the value and rewards of innovation. The benefits are clear.

The future of industrial infrastructure promises to bring new innovations, materials, and techniques to produce higher quality, longer lasting, and more durable infrastructure. Industries such as aluminum, chemical, petrochemical, steel, and others all stand to benefit from the ideas currently moving from concept to reality. These ideas offer the potential for increased corrosion resistance, higher strength, lighter weight, faster application, and less downtime at facilities. New technologies are being introduced that will allow facilities to be continuously self-monitored, with sensor technologies available that are able to detect structural problems, allowing building engineers to prevent serious damage, whether through structural failure or leakage of hazardous materials.

The challenges that lay ahead for industrial infrastructure center around reduction of risks and barriers. There are many obstacles, ranging from economic to regulatory, that must be overcome to take advantage of the myriad opportunities available in innovation. Industry leaders, by joining forces with leaders of the design and construction industry, could be a significant force for change. A collaborative effort working together with regulatory agencies and other government entities could define needed change and determine appropriate legislative measures to remove obstacles to advancements. Initiatives such as carefully constructed liability limiting legislation, enhancement of existing product and technology evaluation and testing programs, new R,D,&D partnerships, and alterations to building codes, where appropriate, could have a dramatic effect on the process and pace of innovation.

The interwoven nature of the businesses, and the fact that new technologies developed by one industry can be used by another for their industrial infrastructure needs, indicates that collaborative action will result in benefits across industry. The benefits in terms of energy savings and environmental protection are immense. The new technologies and materials discussed in this paper present a small fraction of the options that are available for use by industry. The full range of materials and technologies being explored represents an exciting and diverse array of possibilities for the future.

Bibliography

CeraTech, Inc. Pavemend Information Packet, CD-ROM. August, 2002

Civil Engineering Research Foundation (CERF) Highway Innovative Technology Evaluation Center. Evaluation Findings for Seismic Energy Products, L.P. Elastomeric Isolation Bearings. CERF Report #40576, May 2001.

CERF. Environmental Technology Evaluation Plan for Ceracrete Rapid Concrete Repair Technology. January 2001.

CERF Environmental Technology Evaluation Center (EvTEC). Low Range Differential Pressure (LRDP) Leak Detection System Workshop Report. June 2000.

CERF Highway Innovative Technology Evaluation Center (HiTEC). Summary of Evaluation Findings for the Testing of Seismic Isolation and Energy Dissipating Devices. CERF Report #40404, July 1999.

CERF. Commercializing Infrastructure Technologies: A Handbook for Innovators. CERF Report #97-5028. 1997.

CERF. Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems. CERF Report #94-5011, December 1994.

Construction Industry Institute (CII). Emerging Construction Technologies – Electromagnetic Acoustic Transducers (EMAT). www.new-technologies.org/ECT/Other/emat.htm. June 2000.

CII. Emerging Construction Technologies – FRP Rebar. www.new-technologies.org/ECT/Civil/frprebar.htm. January 2002.

CII. Emerging Construction Technologies – Friction Pendulum™: Seismic Isolation Bearings. www.new-technologies.org/ECT/Civil/isobearing.htm. June 2001.

CII. Emerging Construction Technologies – High Performance Steel. www.new-technologies.org/ECT/Civil/hps.htm. June 2000.

CII. Emerging Contruction Technologies – New Infrastructure Repair Method: Fiber Reinforced Plastics. www.new-technologies.org/ECT/Civil/frp_1.htm. June 2000.

CII. Emerging Construction Technologies – SIMCON: Slurry Infiltrated Mat Concrete. www.new-technologies.org/ECT/Civil/simcon.htm. June 2000.

Crucible Materials Corporation. www.cruciblecompaction.com/corrosion.html

Department of Energy - Energy Efficiency and Renewable Energy (DOE-EERE) Industrial Technologies Program. Development of a New Class of Fe-3Cr-W(V) Ferritic Steels for Industrial Process Applications. 2002.

Elliott, Jack & Daniel J. McCarthy. *Continuous Monitoring of Existing Prestressed Concrete Structures: Applications & Results*. American Concrete Institute Convention, April 1998.

Galambos, Theodore, Jerome F. Hajjar, Christopher J. Earls, and John L. Gross. Required Properties of High Performance Steels. NISTIR 6004, May 1997.

Haynes International Hastelloy Corrosion Resistant Alloys. www.haynesintl.com/CRA.html.

Horst, Scott. *Some Basics About Substituting Pozzolans for Portmald Cement in Concrete*. USGBC Member Summit, Tucson, AZ. August 2001.

Humphreys, Ken & Maha Mahasenan. Toward A Sustainable Cement Industry: Substudy 8: Climate Change. World Business Council for Sustainable Development, March 2002.

Krstulovic-Opara, Neven and Mohammed Jamal Al-Shannag. "Slurry Infiltrated Mat Concrete (SIMCON)-Based Shear Retrofit of Reinforced Concrete Members." ACI Structural Journal, January – February 1999. pp. 105 – 114

Krstulovic-Opara, Neven, Erdem Dogan, Chia-Ming Uang, and Abdol R. Haghayeghi. "Flexural Behavior of Composite R.C.-Slurry Infiltrated Concrete (SIMCON) Members." ACI Structural Journal, September – October 1997. pp. 502 – 513

Loehman, Ronald E., Kevin G. Ewsuk, Sylvia M. Johnson, Yigal Blum, William G. Farenholtz, Donald T. Ellerby. *Synthesis and Processing of Composites by Reactive Mental Penetration*. Oak Ridge National Lab, Advanced Industrial Materials Division FY 1998 Progress Report. Pp.55 – 68.

Mistry, Vasant C. *High Performance Steel for Highway Bridges*. Federal Highway Administration (Power Point presentation). Vasant.mistry@fhwa.dot.gov.

Naaseh, Simin, SE. *Practical Solutions for Seismic Isolation Lessons Learned. 5th World Congress on Joints, Bearings, and Seismic Systems for Concrete Structures*. Rome, Italy 7 – 11 October 2001.

Paulson, Peter, Bernard Basile, and Oliver Toszer. *Evaluation of Continuous Acoustic Monitoring as a Means of Detecting Cracking During Stressing of Concrete Structures*. Undated, www.soundprint.com/about_soundprint/technical/containment2.pdf.

Placet, Marylynn and Kim Fowler. Toward a Sustainable Cement Industry: Substudy 7: How Innovation Can Help the Cement Industry Move Toward More Sustainable Practices. World Business Council for Sustainable Development, March 2002.

Reiley, Mike. Personal Communication, February 11, 2003.

Van Ooyen, Kristi. "HPS Success." Modern Steel Construction. September 2002.

Zayas, Victor. "SBIR Awardee Helps Turkey Rebuild With Better Protection Against Future Quakes." NSF Engineering News Online. www.eng.nsf.gov/engnews/2000/Earthquake_Protection/earthquake_protection.htm